EXTRAORDINARY POSSIBILITIES FOR FUTURE CONCRETE STRUCTURES

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ABSTRACT

Concrete, our most widely used construction material, is a fluid that offers the opportunity to economically create structures of almost any geometry. Yet this unique fluidity is seldom capitalised on, with concrete instead being cast into rigid prismatic moulds to create high material use structures with large carbon footprints. This paper will demonstrate how replacing conventional orthogonal moulds with a flexible system comprised primarily low cost fabric sheets can utilise the fluidity of concrete to create extraordinary possibilities for highly optimised, architecturally interesting, building forms.

KEYWORDS

Concrete, fabric formwork, architectural intent, construction, carbon footprint, optimisation.

INTRODUCTION

The language and technology of concrete construction has changed dramatically over the past two thousand years - from the dome of the Pantheon, through its renaissance in the 1800s, and up to the work of Nervi and other modern masters of this fluid material. Throughout this, concrete has been cast almost exclusively into wooden or steel moulds to create prismatic elements. Nervi noted that:

> *'although reinforced concrete has been used for over a hundred years and with increasing interest during the last few decades few of its properties and potentialities have been fully exploited so far...the main cause of this is a trivial technicality: the need to prepare wooden forms' (Nervi, 1956)*

This triviality pervades the minds of Engineers even today, with increased cost being associated with concrete structures that deviate from the use of flat panels of timber or steel as formwork. Despite this, concrete remains one of the most widely used man-made materials in the world, with global production of cement approaching 3.4×10^9t in 2011 (USGS, 2011). Cement accounts for a large proportion of the world's raw material expenditure, reaching nearly 33% of the total in 2008 (Orr, 2012). Although concrete has a relatively low embodied energy (Hammond and Jones, 2011), its rate of consumption means that cement manufacture alone is estimated to account for some 5% of global CO_2 emissions (Orr, 2012).

Figure 1: Possibilities using fabric formwork (Courtesy of Mark West)

Against a backdrop of carbon dioxide emission reduction targets, a recognition of the impact construction has on the environment and an increasing client focus on sustainability, design philosophies centred around the need to put material where it is required are becoming increasingly desirable. Recent research has shown that for concrete structures, large reductions in embodied carbon can be achieved simply by replacing conventional orthogonal moulds with lightweight, high strength, low cost sheets of fabric. This ‘flexible formwork’ not only provides environmental benefits, but also provides a new form of architecture for concrete structures as shown in Figure 1.

The architectural delight of fabric-formed concrete is an additional advantage to the material savings which can be achieved through the structural optimisation processes made possible by the use of a flexible mould. Research undertaken at the Building Research Establishment Centre for Innovative Construction Materials (BRE CICM) at the University of Bath has shown that by following simple optimisation routines and casting concrete into a flexible mould, material savings of up to 40% can be achieved in reinforced concrete beams (Garbett, 2008; Orr, 2012; Orr et al., 2011; Orr et al., 2012c).

In addition to significant material use reductions, research at the BRE CICM has demonstrated that permeable fabric formwork can provide concrete with enhanced durability when compared to concrete cast against an impermeable surface. Significant reductions in carbonation depth and chloride ingress have been recorded (Orr et al., 2012a).

From this, it is apparent that the use of fabric formwork can provide:

- Material use reductions by replacing conventional orthogonal structures with non-prismatic, structurally efficient, alternatives;
- Enhanced durability by the provision of a permeable formwork system;
- New forms of concrete architecture.

Flexible formwork therefore has the potential to facilitate the change in design and construction philosophy that will be required for a move towards a less material intensive, more sustainable, construction industry.

HISTORY

The genesis of fabric formwork can perhaps be found in very early work with reinforced concrete structures, as shown in Gustav Lilienthal’s patents for reinforced concrete flooring systems from the late 19^{th} Century (Lilienthal, 1899). In the 1930s, fabric formwork became a popular method for underwater concrete construction, and remains so today. It was, however, the introduction in the late 1960s of synthetic, high strength, fabrics that led to a second phase in fabric formwork. Initiated by architects such as Miguel Fisac, the new technique was used to create increasingly complex shapes (Fisac, 1969).

More recently, pioneering architectural research been undertaken by Professor Mark West (University of Manitoba), Professor Remo Pedreschi (Edinburgh University) and Kenzo Unno (Japanese architect in Tokyo), amongst many others. A primary research interest at the BRE CICM has been to marry the architectural achievements of fabric formwork with a desire to produce low-carbon concrete structures. This has been achieved by considering the design process afresh. In doing so, numerous challenges and exciting opportunities have been created, some of which are described herein.

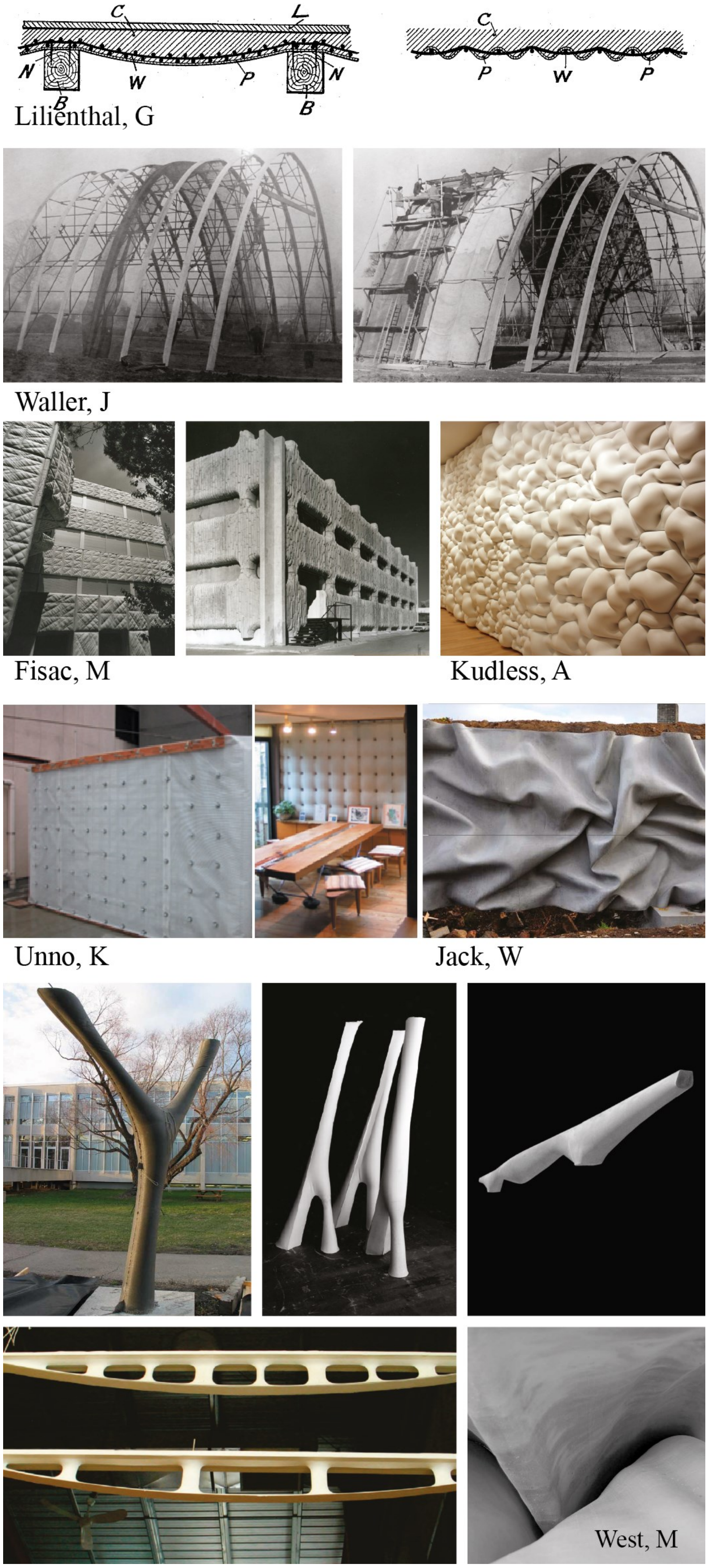

Figure 2: Fabric Formwork. Top to Bottom: Gustav Lilienthal, James Waller, Miguel Fisac, Andrew Kudless, Kenzo Unno, Walter Jack and Mark West. Figure after Orr (2012).

DESIGN AND CONSTRUCTION OF FABRIC-FORMED BEAMS

The main feature of all concrete elements cast in flexible formwork is that their final shape is not known precisely in advance. The cross section of a fabric-formed beam is defined by the deformation of the fabric membrane under the hydrostatic pressure applied by the fresh concrete. Therefore, the cross section of the hardened concrete beam has to be predicted by an appropriate form-finding method for a set of boundary conditions dependent upon the construction approach. In general, the design of fabric-formed beams combines a form-finding procedure with structural analysis, which then can be extended to allow optimisation for defined loading envelopes and geometrical constraints.

From years of experience in casting such structures, it is apparent that hydrostatic shapes can be very efficient in terms of structural performance and material use for depth-to-breadth ratios less than 1.25; however, for deeper sections the bulging effect becomes more pronounced and results in uneconomic design compared with rectangular sections. Thus, in such cases it is necessary to provide a form of lateral restraint to the fabric such as quilt points or web-formers as illustrated in Figure 3. This approach has been tested successfully and is most appropriate for sections subject mainly to bending. Nevertheless, depending on the overall size of the beam element, the concrete flow in the bottom part of the "key-hole" section may be problematic unless high water-to-cement ratio concrete mixes are used. Alternatively, self-compacting concrete can provide better results and has also been investigated.

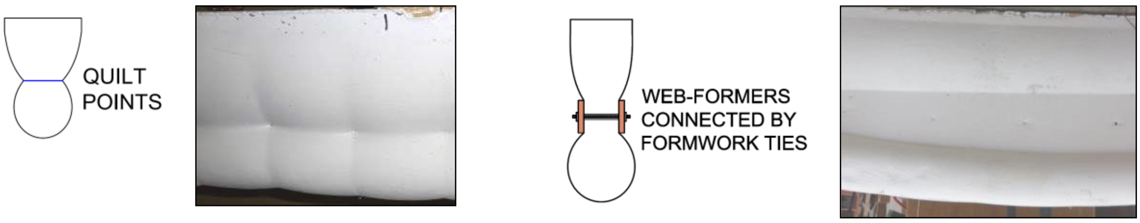

Figure 3: Improved material efficiency of fabric-formed concrete sections

Figure 4 shows a fabric formwork supporting structure used to build a test beam. The fabric is secured longitudinally to the inner edges of the re-usable plywood top plates, which are fixed to laterally-braced frames adjustable in the transverse direction. The system allows easy construction of beams with variable depths up to 400 mm and variable breadths up to 500 mm.

Figure 4: Fabric formwork supporting structure

STRUCTURAL BEHAVIOUR

By replacing orthogonal concrete moulds with a system formed of flexible sheets of fabric it is possible to construct optimised, variable cross section concrete elements that can provide material savings of up to 40% (Orr, 2012) when compared to an equivalent strength prismatic member.

The principle behind the design of beams using fabric formwork is illustrated in Figure 5. This process of optimisation has been applied by the authors to over thirty beam specimens of varying spans and loading conditions (Garbett, 2008, Bailiss, 2006, Orr, 2012). In essence, the optimisation process ensures that at each section along the length of the beam, the resistance of the beam (in flexure, shear, torsion and so on, R_d) matches the requirements of the design envelope (E_d). This simple principle of setting $R_d = E_d$ can create complex shapes – which can then be constructed using the flexible fabric mould. Although much structural testing has focused on beams, this optimisation process (and fabric formwork) can be used for many other structural forms (as seen in work presented in Orr et al (2012c)).

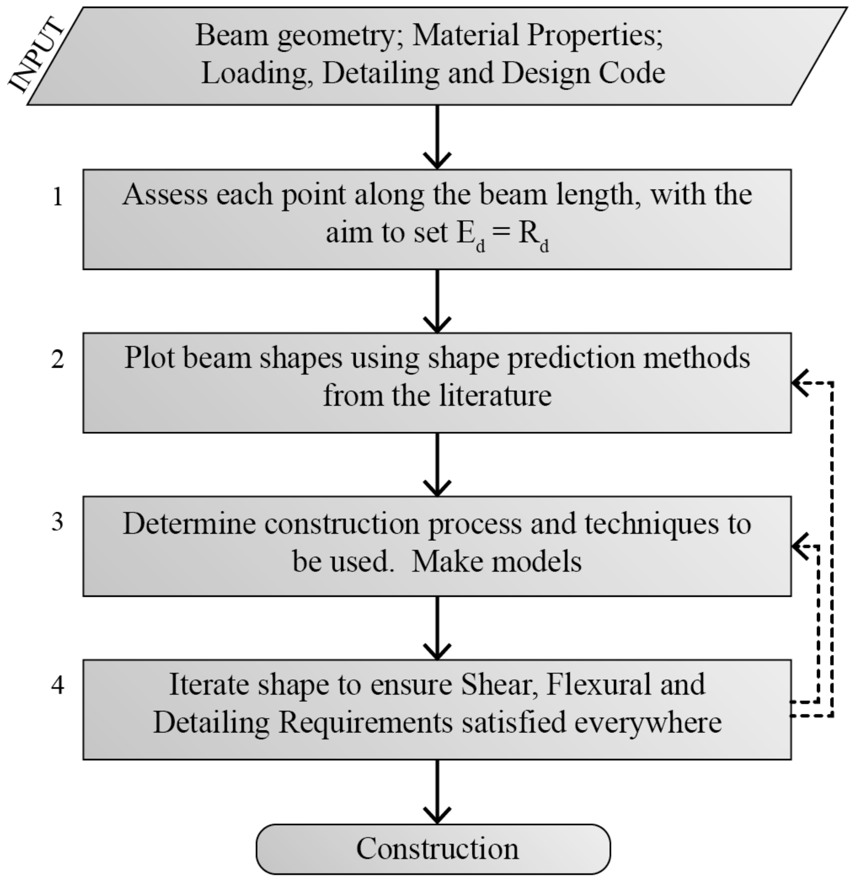

Figure 5: A design process for fabric formed beams

FLEXURE

The flexural design of reinforced concrete relies primarily on the assumption that plane sections before bending remain plane after bending. This assumption forms the basis of most design codes and has been verified through extensive testing to provide a straightforward design method that gives generally unambiguous results (Bentz et al., 2006). As optimised structures are usually not prismatic, the applicability of this approach is not immediately apparent. However, work by Maki and Kuenzi (1965) and later by Davies et al. (1973), as well as work by the authors showing accurate predictions of the flexural strength of non-prismatic beams (Orr, 2012), suggests that it is an acceptable approach for elements with moderate tapers.

SHAPE PREDICTIONS

Accurate shape predictions for fabric cast concrete elements (beams, column, shells and so on) are essential. Scale models (using plaster) have been successful, and new techniques have simply replaced physical models with virtual ones. Methods used include simple spreadsheets which predict the hydrostatic shape of the fluid filled fabric (mathematically explained by Iosilevski (2010)) to more complex computer programs that can automate the entire process (Veenendaal, 2008).

The form-finding approach adopted herein is based on a numerical iterative procedure previously implemented in a Master's dissertation (Foster, 2010). The procedure can be used to find the coordinates of points equally spaced along the length of the fabric i.e. describe fully the cross sectional curve profile. Figure 6 highlights the concept of the procedure using the constant relationship between the hydrostatic height z_i at any given point of the curve and the angle between the tangents to the curve at the same point θ_i, to calculate the coordinates x_i and y_i at each iteration step.

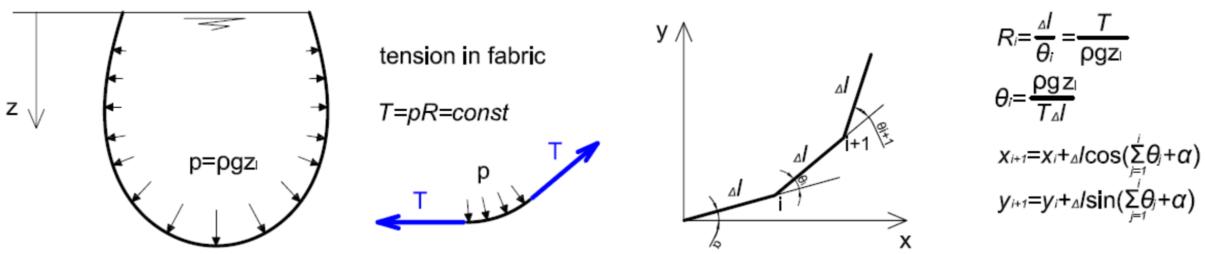

Figure 6: Form-finding procedure

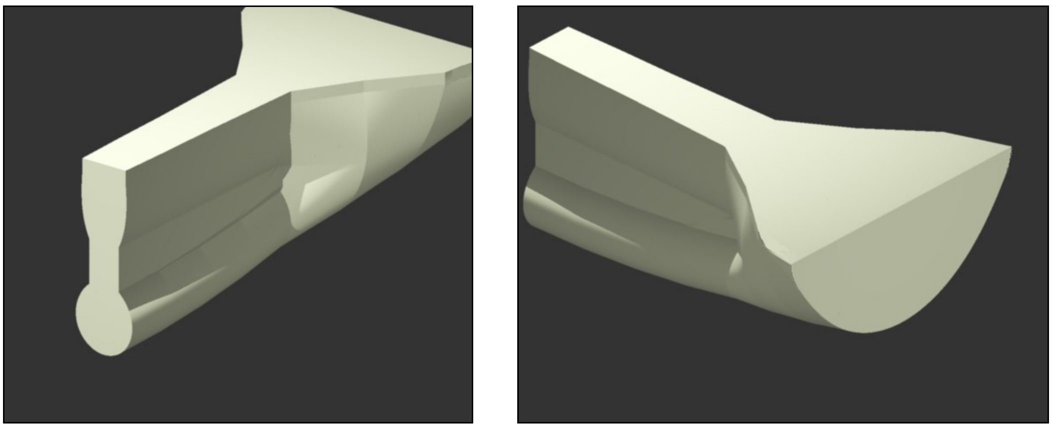

Figure 7: Typical 3-dimensional computer-generated models

The original form-finding procedure has been extended to solve more complex geometries, such as the “key-hole” sections, and has been programmed in MATLAB. Additional codes for sectional analysis use the form-finding output results to perform structural design at a sufficient number of cross sections spaced along the length of a beam. A structural optimisation procedure is then carried out in steps to ensure the optimal longitudinal profile of the variable beam depth, opening breadth or both.

SHEAR

There are a number of contributing factors by which a reinforced concrete beam can carry shear, as described in Figure 8. The relative importance of each factor for prismatic sections is discussed in more detail elsewhere (Kotsovos, 2007, Jelic, 2002). In the steel reinforced section, cracks form when the principal tensile stress in the concrete exceeds its tensile capacity, and inclined cracks typically propagate from the tension face of the member towards the neutral axis as the applied loads are increased. In sections that taper towards their supports, it is imaginable that the interaction of these diagonal cracks with the path of the compression force that reaches the supports is perhaps more critical.

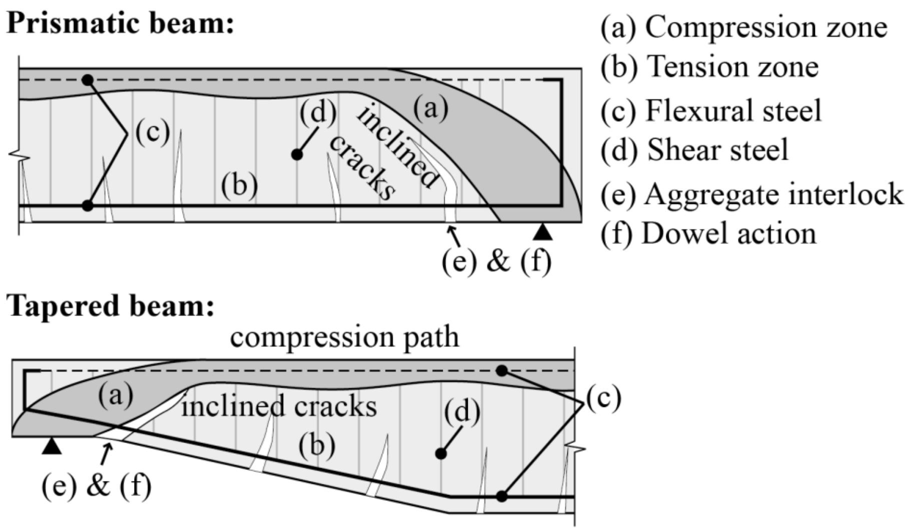

Figure 8: Contributing factors to shear resistance in tapered and prismatic section

Premature failures in shear were recorded in some early optimised beam tests, primarily designed using the empirical provisions of BS 8110 (1997). A test program undertaken by the authors, described by Orr et al (2012b) has begun to address the provision of a design method for tapered beams that does not result in non-conservative capacity predictions and can be used in practice. Using digital image correlation to monitor concrete strains in tapered beams during loading (Figure 9), a better understanding of the behavior of such sections is being developed. This research has shown good results when either the modified Compressive Force Path method, or a strut and tie model, is used.

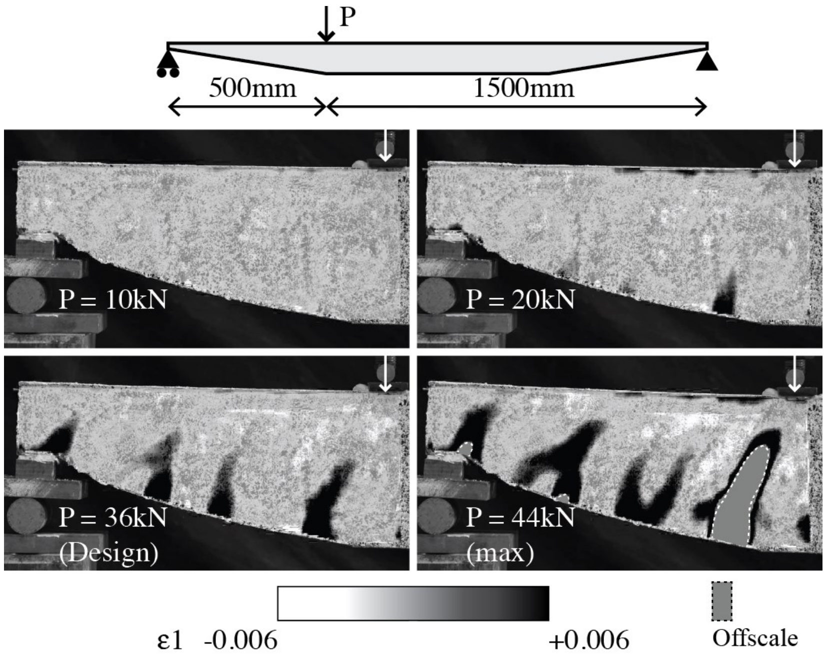

Figure 9: Digital image correlation monitoring the shear behaviour of non-prismatic beams.

TESTING

Beams are tested in the laboratory in order to ensure that bending and shear resistances are achieved, and that geometric tolerances are acceptable. A typical test set-up is shown in Figure 10.

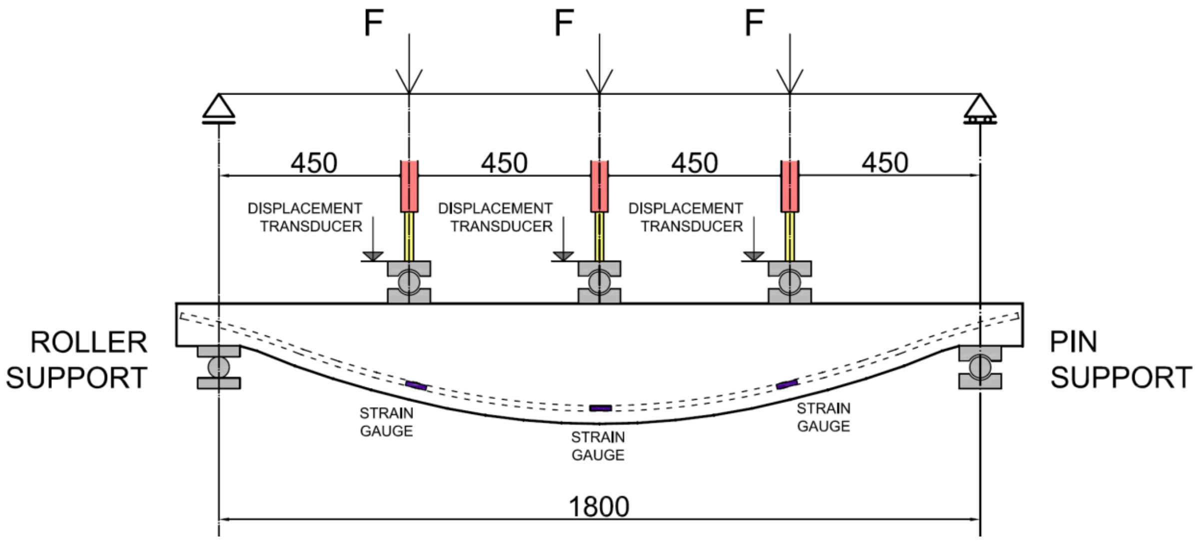

Figure 10: Test set-up

DURABILITY

By allowing water and air to be expelled from a concrete element as it cures, permeable formwork systems such as fabric formwork provide concrete with improved durability due to its denser microstructure and reduced water:cement ratio in the cover zone (Mccarthy et al., 2001). Changes in the surface appearance of such concrete can be seen in Figure 11.

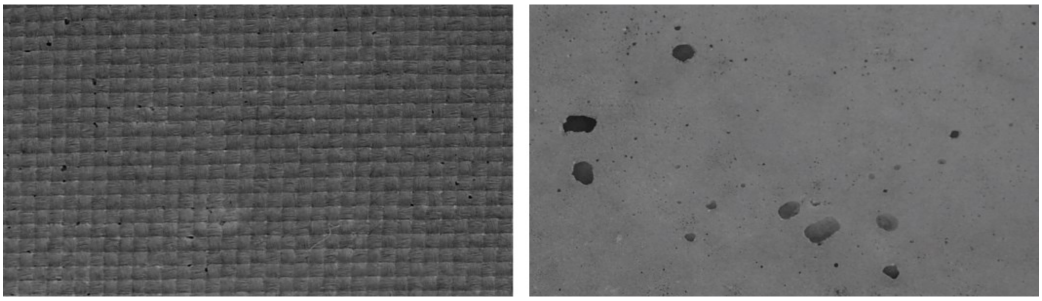

Figure 11: Comparison of concrete cast in a fabric (left) and timber (right) mould

Commercially available permeable formwork systems require the fixing of both permeable and draining layers to the inside of conventional structural formwork. The use of a single flexible fabric formwork system for the creation of optimised, durable structures therefore offers real advantages for designers and contractors. In addition to tests considering structural behaviour, work at the BRE CICM has made use of accelerated testing methods to determine the effect of the permeable mould on durability. To date, carbonation, chloride ingress, surface hardness and sorptivity tests have been undertaken, comparing permeably- and impermeably-cast concrete samples. In addition, scanning electron microscopy has been used to compare the cement contents at the surface of the cast samples.

Carbonation testing, undertaken using NordTest NT 357 (1989), exposed concrete cubes cast against fabric and steel surfaces to carbonation in a chamber of 4% CO_2 for up to 180 days (representing 25 years in service). Chloride ingress testing was undertaken in a similar manner, using a sodium chloride solution with a chloride concentration 5.3 times that of Atlantic seawater. Full details of the tests and their results are provided by Orr et al (2012a). A summary of the improvements seen in this work is presented in Table 1.

Table 1: Summary of durability testing (after (Orr, 2012)) representing tests undertaken on 300 concrete samples.

Test undertaken	Recorded **improvement** using fabric formwork
Carbonation *(Coefficient of Carbonation - (Nordtest, 1989))*	**50%**
Chloride ingress *(Chloride Penetration Parameter, K_{cr} - (Nordtest, 1995))*	**42%**
Surface hardness *(Rebound Hammer – (BS EN 12504-2 (2001))*	up to **13%**

DISCUSSION

Based on experimental and analytical work undertaken at the BRE CICM it is premised that by casting concrete into a fabric mould three effects which serve to improve the durability of the fabric cast concrete occur as air and water are expelled from the mould:

- Finer material collects in the surface zone as water is expelled from the cast surface, resulting in a more tortuous surface layer (see Hall and Hoff, 2002) with fewer interconnected pores;
- A greater concentration of cement particles (or a reduction in the water to cement ratio) at the surface may result in smaller pores to both constrict the flow of gases through the structure of the concrete and provide sites for the formation of Friedel's salt;
- The macroscale surface texture provided to the concrete gives the fabric cast face a greater specific surface area when compared to the timber or steel cast face.

The Carmen-Kozeny equation has been used to begin to describe the relationships between porosity, permeability and specific surface area for fabric cast concrete, but further testing is required to confirm the precise effect of fabric formwork on the internal structure of concrete. Faced with environmental effects, fabric cast concrete shows a number of advantages. A harder surface, as measured using a rebound hammer, suggests locally increased cement content. An increased cement content at the surface is also suggested in data from Scanning Electron Microscopy (Energy-dispersive X-ray spectrography) undertaken on small concrete samples (Orr, 2012).

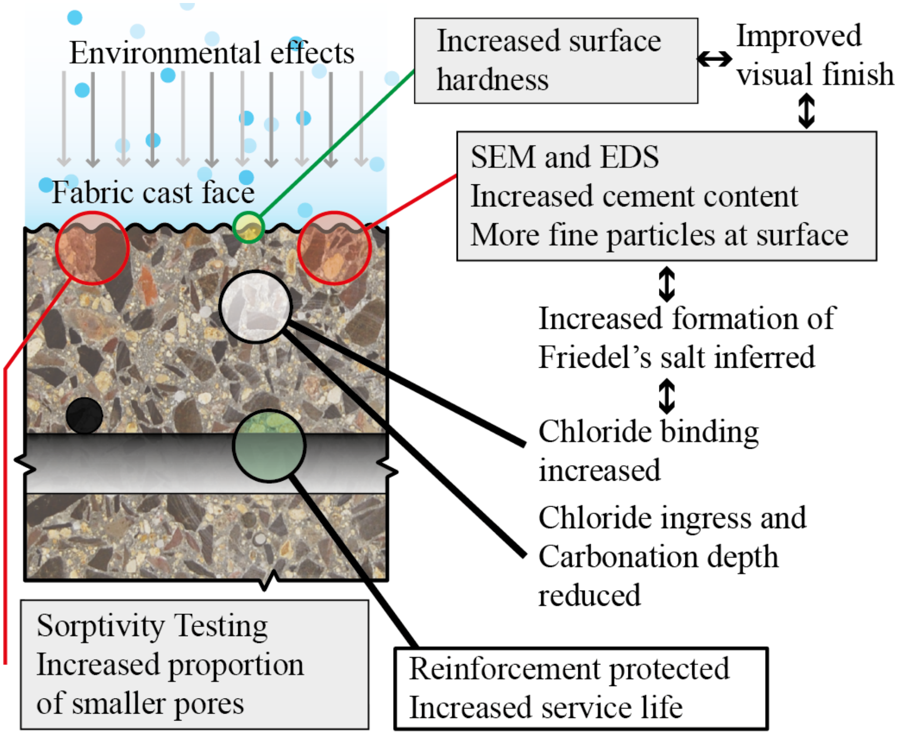

Figure 12: Web of durability advantages found through the use of fabric formwork as a permeable concrete mould

A greater concentration of cement particles at the surface could have the combined effect of constricting the flow of gases through the structure of the concrete (hence providing the resistance to carbonation seen above), while also providing ample sites for the formation of Friedel's salt (which slows the ingress of chlorides). In addition a reduction in the volume of large pores at the surface (as suggested by sorptivity tests) provides a less permeable surface for both carbonation and chloride ingress. These processes thus further retard the corrosion process. Increased chloride binding by this higher cement content also prevents depassivation of the steel, which is thus better protected. This web of potential advantages for fabric formed concrete is illustrated in Figure 12.

ARCHITECTURAL POSSIBILITIES

In addition to the important structural and durability-based advantages of fabric formwork, further possibilities are found in architecture. In teaching, fabric formwork has been successfully used at multiple Universities as a means to consider not only how Engineers and Architects undertake efficient design, but also to 're-think' how concrete itself should be used as a structural material.

In practice, the use of fabric formwork in 'real' projects is, at present, rather limited. Examples, shown in Figure 13 include a Women's hospital in Winnipeg, Canada (by Professor Mark West and Mr Ronnie Araya), shell structures, flat slabs, and columns. All of these elements have been designed and constructed using flexible fabric moulds.

CONCLUSIONS

This paper has summarised some of the recent research undertaken at the University of Bath. Not only is it demonstrated that fabric formwork can be used to create optimised, low carbon concrete structures, but it is also shown that the use of fabric formwork facilitates significant improvements in surface durability. In addition, where the concrete surface is required to provide a visual finish, conventional approaches such as increases in cement content may be avoided through the use of fabric formwork. Instead, the use of a flexible formwork provides both durability and visual benefits.

The majority of testing described here has made use of just one fabric, and further work is currently underway to determine the relative advantages of other available materials in the hope of finding the optimum material that can combine flexibility, a low creep modulus, high strength and a small pore size with low cost. By designing optimised concrete structures, significant savings in material use can be achieved, with concomitant reductions in both embodied carbon and construction cost. Fabric formwork not only provides a simple means by which such structures can be cast, but by allowing excess pore water to bleed from the surface of the concrete the resulting element is both durable and beautiful. Fabric formwork thus offers exciting opportunities for engineers and architects in the move towards a more sustainable construction industry.

Figure 13: A sample of recent fabric formwork projects (images courtesy, clockwise from top left: (West and Araya, 2012, Araya and West, 2012, Belton, 2012, Bhooshan and El Sayed, 2012)

FUTURE WORK

This paper has outlined just some of the work undertaken in the field of flexible formwork. Challenges remain – including the issue of shear behavior in elements with complex shapes, the provision of a full analysis and shape prediction computer model that can be used in industry, and solving some remaining construction difficulties. Areas of future work for fabric formwork include the application of prestressing to the optimisation process, the design and practical construction of flat slabs, permanent formwork systems and precast elements for entire building structures. In addition, the use of low-carbon concretes as an alternative to ordinary Portland cement concretes is an area that could lead to even greater savings in the embodied carbon of fabric formed concrete structures.

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Tim Ibell graduated with a PhD from the University of Cambridge in 1992, and after a couple of years of design experience, completed a post-doc at Cambridge before joining the Department of Architecture and Civil Engineering at the University of Bath in 1997. Tim was promoted to Professor (2003), Head of Department (2005) and Associate Dean of the Faculty (2008). He is the Vice-President of the Institution of Structural Engineers and a Fellow of the Royal Academy of Engineering.

In 2002, Tim spent a year in the US on a Fulbright Distinguished Scholar Award, working with Professor Tony Nanni. Since 2006, Tim has been a member of the EPSRC Peer Review College. He sits on three journal editorial boards, and on several IStructE committees, including Council, Executive Board, Membership, Academic Qualifications Panel (Chair) and the Joint Board of Moderators. He is a Senator at the University of Bath. He has a passion for teaching, particularly at first-year level.

Tim has a strong research interest in the structural behaviour and retrofit of concrete bridges and structures. In particular, Tim is interested in the realistic structural assessment of existing concrete bridges, and he has a team of researchers investigating the use of fibre-reinforced polymers to reinforce and/or strengthen concrete structures. He also leads research into fabric-formed concrete structures, and into the use of polymeric façades for retrofit. Blast resistance of structures (and mitigation) is a growing interest.

He and his team have been the recipients of five best journal-paper awards, including two from the Institution of Civil Engineers and three from the Institution of Structural Engineers.